Acquiring visual information for locomotion by older adults: A systematic review

ABSTRACT

Developments in technology have facilitated quantitative examination of gaze behavior in relation to locomotion. The objective of this systematic review is to provide a critical evaluation of available evidence and to explore the role of gaze behavior among older adults during different forms of locomotion. Database searches were conducted to identify research papers that met the inclusion criteria of (1) study variables that included direct measurement of gaze and at least one form of locomotion, (2) participants who were older adults aged 60 years and above, and (3) reporting original research. Twenty-five papers related to walking on a straight path and turning (n=4), stair navigation (n=3), target negotiation and obstacle circumvention (n=13) and perturbation-evoked sudden loss of balance (n=5) were identified for the final quality assessment. The reviewed articles were found to have acceptable quality, with scores ranging from 47.06% to 94.12%. Overall, the current literature suggests that differences in gaze behavior during locomotion appear to change in late adulthood, especially with respect to transfer of gaze to and from a target, saccade-step latency, fixation durations on targets and viewing patterns. These changes appear to be particularly pronounced for older adults with high risk of falling and impaired executive functioning.

Keywords: *Eye movements, Gaze, Locomotion, Older adults, Review*

1. INTRODUCTION

The percentage of older adults in the overall global population has risen from 9.2% in 1990 to 11.7% in 2013 and is estimated to reach 21.1% by 2050 (United Nations - Department of Economic and Social Affairs (UNDESA), 2013). The social and economic pressures that accompany this demographic trend have highlighted the importance of healthy aging. One of the leading causes of fatal and non-fatal injuries among older adults is falling (World Health Organization, 2007). Besides the increasing costs of associated medical care, falls also have direct negative consequences on the fallers themselves. For instance, fallers are often admitted to hospitals carrying other physical injuries (Aitken et al., 2010; Bell et al., 2000).

Many of the risk factors for falls are considered consequences of the aging process (Kwan et al., 2011), including diminished physical abilities, such as balance, gait, muscle strength (Rubenstein et al., 1996), and reduced levels of mobility (Rantakokko et al., 2013; Studenski et al., 1994). Additionally, increased anxiety and decrements in cognitive resources have also been found to be associated with falling among older adults (Bergland and Wyller, 2004; Holtzer et al., 2007; Persad et al., 1995; van Schoor et al., 2002). For example, older adults who stop walking when talking have been found to have a higher risk of falling (Ayers et al., 2014; Lundin-Olsson et al., 1997). Simultaneously performing two tasks requires more attentional resources and older adults, especially those with decrements in cognitive processing, are more prone to failures in either of the motor or cognitive tasks performed (see (Yogev-Seligmann et al., 2008), for a review). Understanding the impact of the aging process on locomotion is therefore a primary requirement for developing effective falls prevention.

Efficient locomotion is underpinned by a well-coordinated process that involves visual, vestibular, proprioceptive and sensorimotor feedback. It has been argued that visual information dominates such a process (Patla, 1991, 1997, 1998). Specifically, Patla (1997) suggested that visual input is important for employing avoidance strategies, for proactive regulation to ensure stability in dynamic environment, to adjust for different surfaces in the travel path, and to plan the routes for destinations that are not visible from the start. In sum, visuospatial information makes possible preventative regulation of gait patterns that ensure effective and safe locomotion (Patla, 1991). Most falls by older adults occur during locomotion (Prince et al., 1997; Rubenstein, 2006). For example, falls are common when walking on level or uneven surfaces (Berg et al., 1997) or when navigating stairs (Templer et al., 1985), so it is important to understand how vision is used to guide different forms of locomotion in this population.

Studies have examined the importance of visual information during locomotion indirectly by using tests of visual acuity, contrast sensitivity, or directly by occlusion of some part of the visual field (Coleman et al., 2004; Klein et al., 1998). These studies have indicated a relationship between diminished visual abilities and increased risk of falling by older adults. For example, impaired vision is a major independent risk factor for falls in older adults (Freeman et al., 2007; Lord et al., 2010). However, these findings do not elucidate how, or why, impaired visual processing might lead to falling. In order to determine a causal role for vision, it is necessary to study how visual information is extracted from the environment and used for successful navigation.

Visual information necessary for understanding and navigating the environment is directly acquired by eye movements (Hansen and Ji, 2010). Hence, a growing body of research has examined gaze behavior during locomotion. Recent developments in technology have facilitated quantitative examination of gaze behavior, typically in terms of assessing fixations and saccades (Salvucci and Goldberg, 2000). A fixation occurs when gaze rests on a predetermined area for a minimum amount of time, whereas a saccade refers to a fast jump-like movement of the eyes between two fixated areas (Hansen and Ji, 2010). Both gaze parameters have been used to better understand human focus and levels of attention, to quantify cognitive processing and information transfer, and as an indicator of neurophysiologic changes (see (Land, 2006), for a review). Findings have consistently revealed that disruptions of gaze behavior during locomotion are related to age and increased risk of falling. However, to our knowledge, there has been no single published source that offers a critical evaluation of available evidence. Galna et al. (2009) systematically reviewed obstacle crossing in older adults under unconstrained and time-constrained conditions, and Barbieri et al. (2013) investigated (in Portuguese) the effect of ageing on free and adaptive gait behavior. Neither of these studies appraised the importance of gaze behavior. Recently, Higuchi (2013) reviewed visuomotor control of human adaptive locomotion, but did not specifically focus on changes associated with ageing. Consequently, the objective of this review is to synthesize the available evidence on the role of gaze behavior during locomotion (i.e., walking, turning, and stair ambulation) and to examine how such gaze behavior changes as adults age.

2. METHOD

2.1 Search strategy and inclusion criteria

An electronic search of the following databases was conducted within the time period of January 1991 to July 2014: Academic Search Premier, CINAHL Plus, MEDLINE, PubMed Central, Scopus and SportDiscus. The following terms were used: (gaze OR vision OR eye), (walk OR jog OR run OR stair OR ambulation OR locomotion OR gait) and (old OR elder OR aging).

The inclusion criteria were as follows: (1) study variables included direct measures of gaze behavior, (2) study design engaged participants in at least one form of locomotion (e.g., walking, stair negotiation, obstacle avoidance) with free gaze behavior, (3) participants included older adults aged 60 years and above, and (4) reported original research. Studies were excluded when they (1) primarily compared diagnosed patient groups and healthy controls, (2) used a virtual environment or treadmill locomotion in the study design, (3) were published in a language other than English, (4) were a review paper, and (5) were unpublished material such as theses and dissertations. Three independent reviewers performed the examination of search results guided by the four-phase flow diagram of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA; (Moher et al., 2009)). In cases of disagreement, discussions were conducted until a consensus was reached regarding whether the material should be included or excluded in the final list of studies for review.

2.2 Data extraction and quality assessment

The data extraction form retrieved the following information: background/rationale, study objectives and hypotheses, study design and setting, participant selection and characteristics, variables and measurement, findings and conclusions. Data extraction was independently performed by three reviewers, followed by discussion and cross-checking to ensure consistency and accuracy.

No quality assessment instrument has been standardized for laboratory-based observational studies. However, a previous review of research of a similar nature (e.g., gait biomechanics) adapted the Quality Index (Downs and Black, 1998) as an assessment instrument, and added items that were developed to assess the quality of methodology for kinematic analysis (Buldt et al., 2013). In this current systematic review, relevant items from the Quality Index were used, with a total maximum score of 14. Additional items to assess the quality of kinematic methodological variables were adapted from Buldt et al. (2013) and expanded to assess gaze/eye tracking methodology (Hansen and Ji, 2010). The maximum score available for the final quality assessment was 17, as summarized in Table 1. Two reviewers independently performed the quality assessment, and any discrepancies were discussed between raters until consensus was reached.

3. RESULTS

3.1 Search results

In the first stage, the search strategy resulted in retrieval of 3046 citations. After removal of duplicates and screening of titles, 287 abstracts were identified for the second stage. These abstracts were examined using the inclusion/exclusion criteria, yielding 64 papers for full-text review. In the third stage, full-text articles were examined with respect to the objectives of the systematic review. Reference lists were also inspected for other related studies that may have been missed by the electronic search. A final list of 25 articles was identified as suitable for systematic review. Figure 1 illustrates the stages and results of the search process.

3.2 Quality Assessment

Quality assessment results showed a mean score of 71.06%, with a range of 47.06% to 94.12% (see Table 2). Criteria for reporting (items 1-7) were generally met satisfactorily by all of the reviewed studies. However, this was not the case for items 8 and 9, which assessed external validity. These were fully met by only 3 out of 25 reviewed studies. More than half of the studies (13/25) did not report sufficient detail for external validity to be determined. Three studies scored 50% or less on the criteria for internal validity (items 10-15), primarily because they presented insufficient information about the gaze measurement methodology. None of the studies appeared to have fully controlled for confounding factors related to selection bias (items 16-17), and only 10 out of 25 studies met at least one of the two criteria for bias.

3.3 Overview of findings

3.3.1 Walking and turning

Four studies examined gaze behavior and kinematics of walking on a straight path, three of which included turning around a corner or an obstacle (see Table 3). These studies suggested that older adults view the environment differently to younger adults in terms of the use of central and peripheral vision (Itoh and Fukuda, 2002), and the distribution of viewing points (Itoh and Fukuda, 2002; Paquette and Vallis, 2010).

When turning, older adults were found to initiate whole body rotation in tandem with the beginning of a saccade to the direction of the turn, followed by head, trunk and feet re-orientation (Paquette and Vallis, 2010). However, if the direction of the turn was indicated shortly before the turn, older adults initiated the segment reorientation via trunk yaw, followed by rapid shifts of gaze, and then medio-lateral feet displacements. Factoring in the risk of falling, low-risk older adults were shown to have suppressed vestibulo-ocular reflex compared to high-risk older adults (Di Fabio et al., 2001). As well as slower walking speed and longer turning time, older adults were found to have greater side-to-side eye movement compared to the younger participants, both when walking on a straight path and when turning (Petrofsky et al., 2004).

3.3.2 Walking up and down the stairs

Three studies examined visual guidance during stepping up and down locomotion by looking at saccade/stepping interactions in cohorts of older and younger adults (see Table 4). Older adults displayed significantly longer duration between onset of saccade and onset of foot-lift up to the platform (i.e., saccade-step latency) (Di Fabio et al., 2003a). While older adults were also found to have slower speed of stepping on to the platform compared to young adults, saccade/step latency was independent of stepping speed.

When walking up and down stairs, older adults displayed significantly lower cadence and prolonged single stance phase compared to young adults (Zietz and Hollands, 2009). They also fixated longer on the stairs than young adults, and directed their gaze toward the travel path longer. They seldom looked more than four steps ahead, whereas young adults tended to have more widely distributed gaze fixation locations. While a number of older adults used handrails during stair ascent and descent, they did not tend to fixate on the handrail.

Older adults displayed greater fixation time at the step surface compared to young adults but both participant groups directed gaze most often to the step surface, with their range of eye movements being larger vertically than horizontally (Kasahara et al., 2007). In a dark illumination condition, duration of fixation was longer only for the older adults. However, the number of fixations on the steps ahead was greater in light than dark illumination conditions for both older and young adults.

3.3.3 Obstacle circumvention and target negotiation

The most frequently researched tasks were obstacle circumvention and target negotiation, with 13 studies reviewed (see Table 5). In negotiating obstacles, older adults generated preparatory downward and upward saccades prior to stepping over an obstacle as rapidly as young adults, but they required relatively longer saccade/foot lift latency and prolonged gaze fixation time (Di Fabio et al., 2003b). Older adults with low executive function ability displayed relatively larger obstacle contact rate, less frequent down-saccades prior to initiation of the step over an obstacle, and longer cue/saccade latency than older adults with high ability and young adults (Di Fabio et al., 2005).

Both older and young adults fixated the target until heel contact and showed no stepping errors if there was only one target to step on (Chapman and Hollands, 2007). When task difficulty was increased, such as multiple stepping targets, older adults with high risk of falling displayed comparable stepping accuracy, but significantly longer saccade/foot lift latency compared to older adults with low risk of falling (Greany and Di Fabio, 2008). Both low-risk and high-risk older adults also fixated on targets significantly earlier (with respect to toe-off) and for longer durations than young adults (Chapman and Hollands, 2006). However, high-risk older adults fixated on the second target significantly longer than the two other groups, and looked away from the first target significantly sooner with respect to heel contact. This also was the case when the second target required a change of direction (Fontana et al., 2014). Early gaze transfer from the target was associated with an increase in subsequent medio-lateral foot placement variability (Chapman and Hollands, 2006).

When stepping targets were combined with obstacles, high-risk older adults transferred their gaze away from the first target significantly sooner and displayed a higher task failure rate than low-risk older and young adults (Chapman and Hollands, 2007). When rapid responses were required, low-risk, compared to high-risk older adults displayed longer saccadic latency, more fixations, and smaller step widths (Chapman and Hollands, 2010). When stepping targets were combined with distractors, young adults were found to fixate the target more frequently than both high-risk and low-risk older adults (Yamada et al., 2012). In contrast, older adults fixated the walking path more frequently than younger participants.

Given online changes in the location of multiple stepping targets, older adults manifested longer saccadic latency and greater error following medial and lateral changes in target location than young adults (Young and Hollands, 2012). High-risk older adults were worse than their low-risk counterparts when the target moved medially. Furthermore, high-risk older adults tended to look away from the first target sooner than low-risk older and young adults, which was associated with a greater number of missed stepping targets and higher anxiety (Young et al., 2012). A comparison of older adults with and without a history of falling (i.e., fallers vs. non-fallers) showed that fallers displayed a similar pattern of early gaze transfer (Yamada et al., 2011).

Two studies have used interventions to induce changes in gaze behavior and movement kinematics of older adults. Young and Hollands (2010) instructed participants to maintain their gaze on the stepping target until they made heel contact, while Yamada et al. (2013) required participants to practice stepping on multiple targets without specific gaze instructions. Both interventions appeared to facilitate changes in gaze behavior, but in a relatively inconsistent fashion. Post-intervention, participants in the study by Young and Hollands (2010) initiated gaze transfer only after stepping on the target, while those in the study by Yamada et al. (2013) transferred gaze sooner to the next target. Nevertheless, the consistent finding is that both interventions appeared to have improved movement kinematics.

3.3.4 Perturbation-evoked changes in movement kinematics and gaze behavior

Five studies examined gaze during locomotion in the context of online strategies in response to sudden postural perturbations (see Table 6). Older adults took longer to initiate a step after perturbation but rapid step movements occurred when a fixed visual reference was presented (Diehl and Pidcoe, 2010). Neither older or young adults appeared to use 'online' visual feedback when recovering from a loss of balance even when there was an obstacle to avoid or a target to step on (Zettel et al., 2007). Visual scanning of the new environment emerged before perturbation onset, rather than in response to it.

There appeared to be a trend for the older adults to be less likely than the young to initiate a saccade after onset of perturbation. Overall, older adults were not found to have significantly different gaze and walking behaviors in response to perturbations. However, in more complex locomotion tasks, older adults demonstrated increased lateral motion of center of mass, and decreased stepping-on-target accuracy upon introduction of a concurrent visual tracking task (Zettel et al., 2008). Older adults have also been shown to be more likely than young adults to grasp the handrail in response to a perturbation (King et al., 2009). While verbal cueing has been shown to increase attention to the handrail, grasping reactions in response to a perturbation were generally executed without prior visual fixation on the handrail (McKay et al., 2013).

4. DISCUSSION

This review aimed to synthesize the evidence gleaned from studies that had explored the role of gaze behavior by older adults during different forms of locomotion (i.e., walking, turning, stair ambulation). A comprehensive understanding of this topic should yield important insights into prevention of falls among older adults, and thus direct future research efforts.

4.1 Quality Assessment

Most of the reviewed studies met the quality assessment criteria at acceptable levels (>60%). Five studies were found to have poor quality, primarily due to issues of external validity and limited information to confirm internal validity in relation to gaze measurement. Gaze measurement methodology, in particular, is a critical issue because lack of information undermines the validity of measurement of the primary variables of interest in this review. Moreover, it also limits the possibility of replicating the study in order to consolidate stronger evidence. It is therefore recommended that future studies that examine gaze behavior during locomotion should report sufficient detail to support the methodological quality of the gaze measurements that they use.

The most glaring limitation of the reviewed studies was a selection bias, which was caused by inability to determine the criteria concerned rather than by not having met the criteria at all. It is likely that laboratory-based studies simply do not typically report such information. Regardless of whether this is a case of limited reporting or actual study design, it is recommended that to maximize interpretation of study findings, future work in this area should report whether selection bias had been dealt with sufficiently.

4.2 The Role of Gaze Behavior

The importance of different types of visual information for successful locomotion has been established (Higuchi, 2013; Patla, 1997, 1998; Patla and Vickers, 1997). Different kinds of information are required during locomotion for pre-planning (feed-forward), and for on-line control (feedback) (Marigold and Patla, 2007; Patla, 1998, 2003). Gaze behavior represents the mechanism by which visual information is acquired. Pre-planning requires gaze driven assessment of the environment as a precursor to motor planning and movement execution (e.g., an obstacle within view will contribute towards planning an avoidance maneuver). Online control of gaze ensures that relevant visual information is processed *while* locomotion is being performed, enabling appropriate protective responses to be initiated and controlled when necessary (e.g., grab rails within view may offer a response option when balance is perturbed). The studies that we have reviewed consistently show that changes in gaze behavior are associated with aging, which we suggest, reflects age-related gaze adaptations to maintain pre-planning and online control roles of visual information.

Findings from the reviewed studies (Paquette and Vallis, 2010; Petrofsky et al., 2004) confirm locomotion biomechanics to change with age (Bosse et al., 2012; Elble et al., 1991; Judge et al., 1996). Additionally, such changes appear to occur with concurrent adjustments in eye movements and visual focus. Overall, older adults tend to be more dependent on central rather than peripheral vision, and appear to rotate their gaze in order to achieve greater stability. In negotiating obstacles, older adults tend to vary side-to-side eye movements but eventually focus on the ground, presumably to obtain visuospatial information for pre-planning a safe maneuver. It is also possible that the eye movements of older adults change as they adapt to reduced information caused by gradually declining visual function that inevitably accompanies the aging process.

During turning, trunk roll deviations suggest that older adults adjust hip movements in order to control displacements of the center of mass as they veer towards a new direction. It is well established that trunk movements are integral in balancing displacement of the center of mass during locomotion (Winter, 1995). By minimizing head movements during locomotion, a more stable frame of reference for visual focus might be achieved. It is possible that older adults minimize head yaw to enable a visual scan of the environment and to maintain dynamic stability while turning or avoiding an obstacle (i.e., online control).

Kinematic data reported in the reviewed studies suggest that older adults tend to be more cautious during locomotion, as demonstrated by reduced step length and walking speed, presumably to increase gait stability when preparing to avoid an obstacle (Paquette and Vallis, 2010). Walking speed is likely reduced in older adults because of associated prolonged stance time and greater number of steps for a given distance (Petrofsky et al., 2004). Response and movement times increase with age as a consequence of reduced nerve conduction velocity and muscle contractile speed (see (Jagga et al., 2011), for a review), so it is possible that the eye movement changes observed in older adults represent a mechanism that allows visual information to be acquired and processed effectively in the face of altered neuromotor abilities. In other words, eye movements of older adults likely contribute towards allowing them to exercise caution in locomotion, and thereby avoid falling.

While all of the reviewed studies measured eye movements and locomotion kinematics, a clear association was established only for early gaze transfer and stepping errors. In three studies (Chapman and Hollands, 2006, 2010; Young et al., 2012), it was consistently shown that early gaze transfer from the current task location towards an anticipated obstacle was associated with a decrement in stepping accuracy. While older adults have repeatedly been shown to have longer saccade/step latency (Di Fabio et al., 2003a; Di Fabio et al., 2003b; Greany and Di Fabio, 2008; Young and Hollands, 2012), an association with locomotion kinematics is less clear. For example, Di Fabio et al. (2005) reported that greater saccade/step latency was associated with slower stepping velocity, yet Di Fabio et al (2003b) reported no association between saccade/step latency and stepping velocity. While older adults displayed greater saccade/step latency compared to young adults, they nevertheless displayed stepping accuracy no worse than their younger counterparts (Greany and Di Fabio, 2008). In the light of these conflicting findings, future research is warranted to verify the association of saccade/step latency with locomotion kinematics.

4.3 Gaze and Executive Function

While young adults tend to focus their gaze on an obstacle or a wall straight ahead, older adults spend more time gazing at the ground within two steps of an obstacle. Previous studies have shown that older adults have reduced capacity to use online visual feedback rapidly or stored visuospatial information accurately to guide their movements (Chaput and Proteau, 1996; Cheng et al., 2012; Pratt et al., 1994). Due to declines in visuospatial working memory, it is likely that older adults plan the location of their footsteps before and during obstacle circumvention by visually scanning the environment, possibly to ensure a safe path for locomotion. This approach suggests that older adults require more time to process visual information necessary for motor programming in order to perform safe and successful obstacle circumvention.

Prolonged gaze fixation time of older adults when walking up and down stairs is another indicator of longer information processing duration, and has been suggested to be related to declines in executive cognitive functioning. This is also reflected by longer saccade/stepping latency (Di Fabio et al., 2003a) and longer fixations on the stairs before initiating stepping movements (Zietz and Hollands, 2009), compared to younger adults.

Saccades function as a feed-forward guide to the location of the next step, whether it is over an obstacle or onto a platform.

Older adults are able to generate preparatory saccades, but require longer fixation time (Di Fabio et al., 2003a). Moreover, there appears to be a reduction in the frequency of downward saccades that is associated with slowed cognitive processing speed (Di Fabio et al., 2005). Similarly, longer saccade/foot-lift latency was associated with lower executive function ability (Greany and Di Fabio, 2008). Functionally, such changes in saccades could manifest as reduced effectiveness of feed-forward motor control for stepping. Decline in executive cognitive processing has been established as a risk factor for falling and our synthesis of the evidence available suggests that the relationship between executive cognitive function and risk of fall might be explained in part by the slowed processing of visual information, rather than by declining vision.

4.4 Risks of Falling and Fall Prevention

Risks of falling have increasingly been quantified by different forms of physical screening (e.g., Timed Up and Go Test, Berg Balance Scale) and by perceptual measures (e.g., Falls Efficacy Scale, Activities-specific Balance Confidence), allowing recent studies to compare older adults at high as opposed to low risk of falling. Consistently, the evidence suggests that high-risk older adults display changes in gaze behavior to a larger extent than low-risk older adults (Chapman and Hollands, 2006, 2007, 2010; Greany and Di Fabio, 2008; Yamada et al., 2012; Young et al., 2012). Particularly when there are multiple targets or obstacles, early gaze transfer occurs even sooner among high-risk relative to low-risk older adults (Chapman and Hollands, 2010). That such early gaze transfer is associated with increased probability of missing steps suggests a strong relationship between gaze behavior and performance among high-risk older adults, but the causality remains unclear.

It might be the case that high-risk older adults miss steps due to non-visual aspects of motor control (e.g., proprioception, strength) and early gaze transfer is a means to anticipate potential stepping errors. It has been shown that foot placement errors can be reduced by instructing older adults to maintain their gaze on a stepping target until heel contact (Young and Hollands, 2010). While this indicates a direction of causality, limitations of study design (i.e., small sample size, limited ecological validity) suggest that there is a need for replication with more representative and bigger samples, and in non-laboratory environments. Essentially, further research is warranted to investigate the possibility that gaze behavior and locomotor training may be a promising approach for minimizing risk of falling by older adults.

People tend not to use 'online' visual feedback to recover from loss of balance, even when there is an obstacle to avoid or target to step on, as demonstrated by limited visual scanning of the environment in response to a perturbation stimulus (Zettel et al., 2007). This suggests that visual information obtained under normal conditions (i.e., before the perturbation) is critical for determining a person's ability to respond to an unexpected change in the environment, and thus not to fall. Older adults who score high on subjective indices of fall risk also tend to be more conscious of their movements (Wong et al., 2008, 2009). The propensity for conscious monitoring and control of movement is referred to as movement-specific reinvestment (Masters, 1992; Masters and Maxwell, 2008) and it is possible that older adults who are more conscious of their movements tend to reinvest more cognitive resources in monitoring their movements. With reduced visuospatial working memory capacity (Cheng et al., 2013), reinvestment could potentially limit older adults' ability to extract pertinent visual information from the environment. Whether such personality characteristics interact with gaze behavior and risk of falling could be explored in future research, potentially contributing to fall prevention programs.

4.5 Limitations

The findings of this review should be interpreted with consideration of a number of limitations. There is a wide range of quality assessment scores among the reviewed studies, and, in particular, studies that scored low on external validity may limit generalizability of the findings. Studies that scored lower on internal validity did not report gaze measurement methodology clearly, potentially undermining the internal validity of the reported findings. Nevertheless, we included these studies in the review to enable a comprehensive synthesis of the evidence. Although not included in the quality assessment, it should be noted that very small sample sizes in some studies (e.g., 4-6 participants in one experimental group) might have influenced the validity and reliability of their findings. Power calculations are highly recommended for future studies.

This review did not specifically aim to examine the evidence concerning the impact of corrective lenses on gaze behavior and locomotion kinematics. Nevertheless, it is acknowledged there is some research indicating differences in walking speed and obstacle avoidance when wearing multi-focal or single-lens glasses (e.g. Menant, St. George, Sandery, Fitzpatrick, & Lord, 2009). Most currently available gaze tracking equipment does not accommodate spectacles, so future research in this area is imperative to fully understand the relationship between gaze behavior and locomotion.

Finally, this review does not offer a quantitative summary (i.e., meta-analysis) of the relationships due to the varied study designs of the reviewed articles and unavailability of necessary statistics, such as effect sizes (reported for 4 out of 25 studies).

5. CONCLUSIONS

This review offers a synthesis of available evidence that informs mechanisms by which older adults acquire visual information from the environment during locomotion. It is clear that gaze behavior changes in older adulthood, particularly with respect to gaze transfer, saccade/step latency, fixation time and viewing patterns. Such changes are heightened in older adults at high risk of falling or who have impaired executive cognitive function. Consistently, the evidence shows that early gaze transfer has a detrimental effect on stepping accuracy, and some indicators suggest that saccade/step latency influences stepping velocity. Overall, the research findings point to the limited use of online visual information in response to unexpected threats to locomotion stability, highlighting the need for older adults to be aware of the visual environment prior to initiation of locomotion.

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FIGURE CAPTIONS

Figure 1. Stages and results of the search process. Adapted from (Moher et al., 2009).

TABLES

Table 1. Quality assessment items

Category	Item number	Item
Reporting	1	Is the hypothesis/aim/objective of the study clearly described?
	2	Are the main outcomes to be measured clearly described in the Introduction or Methods section?
	3	Are the characteristics of the patients included in the study clearly described?
	4[a]	Were movement tasks clearly described?
	5	Are the main findings of the study clearly described?
	6	Does the study provide estimates of the random variability in the data for the main outcomes?
	7	Have actual probability values been reported for the main outcomes except where the probability value is less than 0.001?
External validity	8	Were the subjects asked to participate in the study representative of the entire population from which they were recruited?
	9	Were those subjects who were prepared to participate, representative of the entire population from which they were recruited?
Internal Validity	10[a]	Was equipment for measurement of gaze clearly described, including validity, reliability and accuracy indices?
	11[b]	Were gaze outcome measures well defined (e.g. definition of fixation)?
	12[b]	Was data processing of gaze data clearly described?
	13	Were the statistical tests used to assess the main outcomes appropriate?
	14	Were the main outcome measures used accurate (valid and reliable)?
	15[c]	Was there a control group of young adult participants?
Internal Validity (Confounding)	16	Were the participants in different groups (older and young adults) recruited from the same population?
	17	Were study participants in different groups (older and young adults) recruited over the same period of time?

Notes: Items were taken from the Quality Index (Downs and Black, 1998), unless otherwise specified.
[a] *Methodological quality of laboratory-based studies (Buldt et al., 2013).*
[b] *Verification of gaze estimation methodology (Hansen and Ji, 2010)*
[c] *Additional item to verify presence/absence of control group.*

Table 2. Quality assessment scores

Articles	Items																	Total	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Raw	%
(Di Fabio et al., 2001)	1	1	1	1	1	1	1	1	U	1	1	1	1	1	0	1	U	14	82.35
(Itoh and Fukuda, 2002)	1	1	1	1	1	1	0	1	U	0	0	0	1	1	1	1	U	11	64.71
(Di Fabio et al., 2003a)	1	1	1	1	1	1	1	U	U	1	0	1	1	1	1	U	U	12	70.59
(Di Fabio et al., 2003b)	1	1	1	1	1	1	1	U	U	1	0	1	1	1	1	U	U	12	70.59
(Petrofsky et al., 2004)	1	1	1	0	1	1	0	U	U	1	0	0	1	1	1	U	U	9	52.94
(Di Fabio et al., 2005)	1	1	1	1	1	1	0	U	U	0	0	0	1	1	1	U	U	9	52.94
(Chapman and Hollands, 2006)	1	1	1	1	1	1	0	U	U	1	1	0	1	1	1	U	U	11	64.71
(Chapman and Hollands, 2007)	1	1	1	1	1	1	0	U	U	0	1	0	1	1	1	U	U	10	58.82
(Kasahara et al., 2007)	1	1	1	1	1	1	0	U	U	0	1	1	1	1	1	U	U	11	64.71
(Zettel et al., 2007)	1	1	1	1	1	1	1	U	U	1	0	0	1	1	1	U	U	11	64.71
(Greany and Di Fabio, 2008)	1	1	1	1	1	1	1	1	U	1	0	1	1	1	0	1	U	13	76.47
(Zettel et al., 2008)	1	1	1	1	1	1	1	U	U	1	1	1	1	1	1	U	U	13	76.47
(King et al., 2009)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	U	16	94.12
(Zietz and Hollands, 2009)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	U	15	88.24
(Chapman and Hollands, 2010)	1	1	1	1	1	1	1	U	U	0	1	0	1	1	1	U	U	11	64.71
(Diehl and Pidcoe, 2010)	1	1	1	1	1	1	1	1	U	1	1	1	1	1	1	U	U	14	82.35
(Paquette and Vallis, 2010)	1	1	1	1	1	1	1	1	U	1	1	1	1	1	1	U	U	14	82.35
(Young and Hollands, 2010)	1	1	1	1	1	1	0	U	1	1	1	1	1	1	0	1	U	13	76.47
(Yamada et al., 2011)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	U	15	88.24
(Yamada et al., 2012)	1	1	1	1	1	1	0	U	U	1	1	1	1	0	1	U	U	11	64.71
(Young and Hollands, 2012)	1	1	1	1	1	1	0	U	U	1	0	0	1	1	1	U	U	10	58.82
(Young et al., 2012)	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	1	U	13	76.47
(McKay et al., 2013)	1	1	1	1	1	1	1	1	U	1	1	1	1	1	0	1	U	14	82.35
(Yamada et al., 2013)	1	1	1	1	0	1	1	1	U	1	1	0	1	1	0	1	U	12	70.59
(Fontana et al., 2014)	1	1	1	1	1	1	0	U	U	0	0	0	1	U	1	U	U	8	47.06

Overall mean	12.08	71.06

Note: U – Unable to determine

Table 3. Summary of studies that examined gaze and locomotion kinematics when walking on a straight path and turning

Article	Sample	Locomotion	Gaze Parameter(s)	Main Finding(s)
(Di Fabio et al., 2001)	36 older adults (71-88 yr) 18 high risk of falling 18 low risk of falling	Walking straight for three steps	Horizontal and vertical eye motion with respect to the head	Low-risk older adults tended to direct their gaze in the same direction as the head and trunk pitch High-risk older adults tended to direct their gaze in the opposite direction as the head and trunk pitch
(Itoh and Fukuda, 2002)	6 older adults (63-72 yr); 6 young adults (19-32 yr)	Walking straight over 32 meters	Gaze direction Viewing area Eye movement velocity	Viewing points of young adults fall within eye level; older adults below eye level Older adults are highly dependent on central vision; young adults include use of peripheral vision
(Petrofsky et al., 2004)	44 participants (10-68 yr) 4 age groups: 10-19 years 20-39 years 40-59 years 60-75 years	Walking and turning with turn diameters of 0.33 and 0.66 m	Coefficient of variation of side-to-side eye movements	Greater side-to-side eye movement variation for the oldest age group in both walking straight and turning Significant increase in side-to-side eye movement variation in the 40-59 y/o age group compared to the two younger groups during turning
(Paquette and Vallis, 2010)	6 older adults (74.5±2.3 yr) 6 young adults (20.3±0.8 yr)	Walking around an obstacle	Gaze area of interest	Older adults spent more time gazing at the ground within two steps prior to an obstacle Young adults focused their gaze on the obstacle or the wall straight ahead even when a late visual cue is given during a circumvention task

Table 4. Summary of studies that examined gaze and locomotion kinematics when navigating stairs

Article	Sample	Locomotion	Gaze Parameter(s)	Main Finding(s)
(Di Fabio et al., 2003a)	4 older adults (84-93 yr) 5 young adults (23-25 yr)	Stepping up onto a platform	Vertical eye movements Saccades	Both older and young adults initiate saccade in advance of stepping Older adults show prolonged saccade-step latencies indicative of a delay in information processing
(Kasahara et al., 2007)	4 older adults (70.3±7.3 yr) 5 young adults (23.6±1.9 yr)	Stair descending in light and dark illumination conditions	Eye position Movement amplitudes Duration of fixation Number of fixations Tracking velocity	Older adults tend to use more central vision, restricting the range of eye movements, in ensuring safe stepping behaviors The range of eye movements was larger vertically than horizontally for both older and young adults Older adults increased fixation duration during stair descent in a dark illumination condition
(Zietz and Hollands, 2009)	10 older adults (70.7±3.1 yr) 10 young adults (21.4±2.2 yr)	Stair descending and ascending	Fixation location Fixation duration	Before stepping onto stairs older adults were found to fixate the stairs longer indicative of changes in information processing speed Both age groups fixated approximately three stairs ahead in both walking directions

Table 5. Summary of studies that examined gaze and locomotion kinematics during obstacle circumvention and target negotiation.

Article	Sample	Locomotion	Gaze Parameter(s)	Main Finding(s)
(Di Fabio et al., 2003b)	4 older adults (84-93 yr); 5 young adults (23-25 yr)	Walking and stepping over an obstacle	Vertical eye movements Gaze angle Saccadic latency Duration of fixations	Older adults showed fewer preparatory saccades and prolonged saccade-trailing-footlift latencies
(Di Fabio et al., 2005)	35 older adults (74-94 yr): 20 high executive function 15 low executive function 15 young adults (21-25 yr)	Walking and stepping over three obstacles	Saccadic latency	Older adults with low executive function displayed greater obstacle contact rate, prolonged cue-saccade latency and fewer down-saccades than older adults with high executive function and young adults
(Chapman and Hollands, 2006)	8 older adults (66-71 yr): 4 high risk of falling 4 low risk of falling 8 young adults (24.8±4.1 yr)	Walking and stepping on a target	Duration of fixations Saccadic latency Gaze transfer	High risk of falling older adults transferred gaze away from the target earlier and displayed higher foot placement variability than young adults and low risk of falling older adults Older adults needed more time to plan stepping movements and future actions than young adults
(Chapman and Hollands, 2007)	12 older adults: 6 high risk of falling 6 low risk of falling 6 young adults	Walking and stepping on a target and stepping over an obstacle	Duration of fixations Saccadic latency Gaze transfer	Under a single target condition all participants fixated on the target until after heel contact Under more complex conditions high risk of falling older adults demonstrate earlier gaze transfer which was associated with decline in stepping accuracy
(Greany and Di Fabio, 2008)	30 older adults (74-95 yr): 15 high risk of falling 15 low risk of falling	Walking and stepping on a target	Saccadic latency	High risk of falling older adults showed significantly longer saccade-footlift latencies than low risk of falling older adults
(Chapman and Hollands, 2010)	20 older adults (65-85 yr): 10 high risk of falling 10 low risk of falling 10 young adults (22-30 yr)	Walking and stepping on a target	Saccadic latency Number of fixations Duration of fixations	Older adults, particularly high risk of falling older adults, require more time to initiate, plan and execute stepping adjustments

Article	Sample	Locomotion	Gaze Parameter(s)	Main Finding(s)
(Young and Hollands, 2010)	16 older adults (65+ yr)	Walking and stepping on a target and over an obstacle	Saccadic latency Duration of fixations Gaze transfer	Following gaze intervention (preventing early gaze transfer), older adults delayed gaze transfer until heel contact and this was associated with reduction in stepping errors
(Yamada et al., 2011)	18 older adults (71-88 yr): 9 fallers 9 non-fallers	Walking and stepping over an obstacle under single task and dual task conditions	Number of saccades Duration of fixations Gaze transfer	Fallers and non-fallers showed similar gaze patterns under single-task conditions Under dual-task conditions fallers demonstrated earlier gaze transfer than non-fallers showing preference to plan future movements
(Yamada et al., 2012)	37 older adults (78±6.8 yr): 11 high risk of falling 26 low risk of falling 20 young adults (21.1±1.4 yr)	Walking and stepping on a target	Location of fixations Duration of fixations	Young adults fixated around three steps ahead whereas older adults, especially high risk of falling, fixated closer to the target, which impaired future step planning High risk of falling older adults demonstrated higher rate of stepping and avoidance failures
(Young and Hollands, 2012)	16 older adults (68-83 yr): 8 high risk of falling 8 low risk of falling 8 young adults (21-30 yr)	Walking and stepping on a target	Saccadic latency	All participants, but especially high risk of falling older adults, were less accurate when making medial compared to lateral stepping adjustments High risk of falling older adults made less consistent stepping adjustment than low risk older adults and young adults Differences in final foot placement errors could be explained by differences in saccadic response times
(Young et al., 2012)	17 older adults (67-83 yr): 9 high risk of falling 8 low risk of falling	Walking and stepping on a target and over an obstacle	Saccadic latency Gaze transfer Duration of fixations Number of fixations	High risk of falling older adults reported higher levels of anxiety, earlier gaze transfer, and increased stepping inaccuracy in response to increased locomotor task complexity
(Yamada et al., 2013)	264 older adults (65+yr)	Walking and stepping on multiple targets	Location of fixations Gaze initiation Gaze termination	Following intervention, older adults showed, earlier gaze initiation and termination, higher tendency to fixate toward a future target, and

Article	Sample	Locomotion	Gaze Parameter(s)	Main Finding(s)
				improved stepping accuracy than control participants.
(Fontana et al., 2014)	12 older adults (77.2±8.7 yr): 6 high risk of falling 6 low risk of falling 6 young adults (20.3±0.8 yr)	Walking and stepping on multiple targets	Duration of fixations Saccadic latency	High risk of falling older adults transferred gaze away from the target before making heel contact with the target whereas low risk older adults and young adults after making heel contact

Table 6. Summary of studies that examined gaze and locomotion kinematics before and after perturbation-evoked sudden loss of balance

Article	Sample	Locomotion	Gaze Parameter(s)	Main Finding(s)
(Zettel et al., 2007)	10 older adults (60-76 yr); 12 young adults (22-33 yr)	Inducing forward-step reactions	Downward gaze shifts Number of saccades Number of fixations	The recovery from the sudden loss of balance is initially modulated by the visuospatial information about the environment acquired and updated prior to perturbation onset The ability to do it was not negatively affected by age
(Zettel et al., 2008)	6 older adults (61-68 yr) 18 young adults (22-30 yr)	Inducing forward-step reactions	Downward gaze shifts	Both older and young adults directed gaze downwards more often in no-tracking trials Tracking trials led to increased center-of-mass motions in older adults
(King et al., 2009)	12 older adults (64-79 yr); 12 young adults (22-30 yr)	Inducing a backward falling motion	Number of fixations Number of saccades	Older adults did not direct their gaze to the handrail when entering the new environment but were twice as likely as young adults to grasp the handrail to recover from perturbation Grasping errors were common
(Diehl and Pidcoe, 2010)	10 older adults (71.9±8.9 yr) 10 young adults (27.4±5.1 yr)	Inducing an anteriorly directed postural perturbation	Percent foveal fixation	Older adults took longer to initiate a step than young adults Older and young adults initiated quicker steps when percent of foveal fixation was high Young adults were more successful in maintaining fixation on the target when perturbation was evoked
(McKay et al., 2013)	160 older adults (64-80 yr)	Inducing a backward falling motion	Number of fixations	Verbal cuing attracted overt visual attention to handrail and increased proactive handrail use